CENTRE FOR COLD OCEAN RESOURCES ENGINEERING

SEDIMENTATION TUBE

USER MANUAL

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C-CORE

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The Centre for Cold Ocean Resources Engineering (C-CORE) was established at Memorial University of Newfoundland in 1975. Its initial funding was provided by the Devonian Group of Charitable Foundations in Calgary, Alberta. Ongoing funding now comes from government and industry.

The Centre's mandate is to undertake research that will assist the safe and orderly development of Canada's resources in cold and ice frequented oceans.

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ABSTRACT

The Centre for Cold Ocean Resources Engineering Settling Tube is an automated system designed for the efficient and rapid analysis of unconsolidated sand size sediment. The system exhibits excellent reproducibility and accuracy, and has significantly higher resolution than the conventional mechanical sieve method. Total sample analysis takes approximately 15 minutes and can be successfully carried out on samples of 0.5 to 15 g (dry weight), to a minimum diameter of 63 microns.

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INTRODUCTION

Grain-size analysis of unconsolidated sediment in the -1 to 4 phi size range is a basic procedure in sediment studies which to date has most commonly been undertaken by mechanical sieving. The resultant sediment grain-size data is utilized to quantify sediment populations for purposes of comparison, and, more significantly, to attempt to identify and describe depositional processes and/or sedimentological environments (Folk and Ward, 1957; Visher, 1969; Bridge, 1981); but see Christiansen 'et al.' (1984). An updated assessment of methodologies of grain-size measurements by sieving and other techniques has been reviewed recently by Komar and Cui (1984). The most obvious advantage of sieving is that it is a standardized procedure with a reasonable degree of precision (reproducibility) which has wide currency in both industrial and academic institutions and, therefore, results can be compared easily. The disadvantage is that it is difficult to determine exactly which physical properties of the sediment grains are being measured. Intuitively, it would appear to be some combination of size and shape of the sediment grains. Hence, the degree of accuracy of the method is certainly arguable.

As an alternative to sieving, measurement of the settling velocity of sand size sediment particles has steadily increased in popularity during the past two decades (Schlee, 1966; Nelsen, 1976; Amos 'et al.', 1981). The basic assumption underlying this method is that the settling velocity of a particle is a more fundamental dynamic property than any geometrically defined

measure of size with reference to its behaviour in a hydrodynamic environment. For instance, it is well known that the initiation of motion as well as the concentration and distribution of suspended sediment in a fluid are directly dependent on the ratio between shear velocity and settling velocity (Middleton and Southard, 1978). Hence, settling velocity distributions, and grain size distributions derived from them are more valid than sieve size distributions when modelling flow conditions at the time of deposition (Middleton, 1976; Bridge, 1981), and are more sensitive to the subtle interaction of grain size, shape and density in different depositional environments (Reed 'et al'., 1975).

Other advantages of sediment settling tubes over the standard mechanical sieving method for the analysis of sand are:

1) the data are directly compatible with data in the silt-clay size range which is also analysed by settling (pipette or sedigraph method);
2) the measurement process is continuous and much more data is available than in the case of sieving, which is discontinuous;
3) the adaptation of modern detection systems and automated data processing enables rapid analysis of a large number of samples in a short period of time.

Since the settling tube method can only analyse grains in the -1 to 4 phi size range, it therefore becomes necessary to analyse the coarse and fine tails of a sample via alternate means (i.e. sieving for coarser fractions and pipetting for finer

fractions). Unfortunately, it is generally believed that the information most useful for interpretation of sedimentological environments and depositional processes is contained in the tails of the size distribution (Blatt, 'et al.', 1972). Although this is a drawback to the settling method, it applies equally to the mechanical sieve method which also relies on pipetting for analysis of the fine fraction.

PARTICLE SETTLING THEORY

Movement of a solid body through a fluid is opposed by forces exerted by that fluid. These forces are of two types - viscous and inertial. Inertial resistance is a direct consequence of the necessity for the moving body to displace the fluid as it passes and is therefore proportional to the mass density of the fluid. It has been found experimentally that inertial resistance is itself a function of viscous forces. Viscosity is a property of all fluids which has its origin in intermolecular forces and varies directly with temperature and concentration of dissolved salts. The ratio of inertial to viscous force is expressed by a Reynolds number (**Re**) which is a dimensionless expression of the fundamental properties of a given hydrodynamic system, namely velocity (**v**), fluid density (ρ), viscosity (μ) and some measure of length such as the diameter of the particle (**d**). Reynolds number is expressed by the formula;

$$Re = vd\rho/\mu \qquad (1)$$

Hence, the force of resistence on a particle moving through a fluid depends on its size and velocity and on the density and

viscosity of the fluid. Stokes (1851) formulated a relationship expressing the settling velocity of a single solid sphere in fluid as;

$$w_s = \left[\frac{(\rho_s - \rho)g}{18\mu}\right]d^2 \qquad (2)$$

where w_s is the settling velocity of the sphere, ($\rho_s - \rho$) is the density difference between the particle and the fluid, **g** is the force of gravity, is the viscosity of the fluid and **d** is the sphere diameter. Experimentally Stokes' Law is found to be valid only at low Reynolds numbers (< 1) and, therefore, small particle sizes (< 50 microns). Natural sediment particles in this size range are rarely spherical and therefore the "size" measured by settling techniques is actually an "equivalent diameter", derined as the diameter of a quartz sphere having the same settling velocity as the particle.

For particles which do not follow Stokes' Law (i.e. fine to coarse sand size) a number of formulae and empirical curves have been proposed (see Rubey, 1933; Rouse, 1937; Graf and Acaroglu, 1966; Watson, 1969). The most widely used formula for settling analysis of sand size particles is that given by Gibbs 'et al'., (1971) which gives the settling velocity of a sphere of radius **r**;

$$w_s = \frac{-3\mu + \sqrt{9\mu^2 + gr^2\rho(\rho_s - \rho)(0.015476 + 0.19841r)}}{\rho(0.011607 + 0.014881r)} \qquad (3)$$

This equation was derived from data obtained by settling glass spheres of various sizes and known density. It allows for correction and standardization of data for varying temperature,

viscosity, fluid density and particle density, and is easily adaptable to automated data processing. A rearrangement of equation (3) may be used to calculate sphere size from measured settling velocity as follows:

$$r = 0.055804W_s^2\rho + \frac{\sqrt{0.003114W_s^4\rho^2 + \{g(\rho_s - \rho)\}\{4.5\mu W_s + 0.0085W_s^2\rho_s\}}}{\{g(\rho_s - \rho)\}} \quad (4)$$

Since natural sand grains are rarely, if ever, spherical they invariably settle at a velocity which is less than would be expected for a sphere of equivalent size (defined as a sphere whose diameter equals the intermediate diameter of the particle). Baba and Komar (1981) have shown this to be due to irregularities in grain shape (nonsphericity and asymmetry) rather than grain roundness (angularity). They propose an equation which may be used to correct for this aberrancy;

$$W_m = 0.977W_s^{0.913} \quad (5)$$

where W_m is the measured settling velocity.

While the above formulations may accurately describe single solid grains settling in water, none except Stokes' equation at low velocities adequately describe the relationship between mean grain size and median settling velocity of multigrain samples. As such, their application to settling tube analysis of sand entails certain discrepancies which arise largely from a group of effects produced by the necessity of introducing a relatively high concentration of sediment at the top of the tube which must

then become stratified as it settles. These concentration effects include:

a) hindered settling (the measured settling velocity, W_m, is less than the theoretical settling velocity, W_s due to the counterflow of suspending fluid upward through the falling sediment);

b) settling convection (vortices and pressure gradients created in the sedimentation fluid by movement of particles), and

c) mass settling (smaller grains are dragged down by the larger grains).

Kranenburg and Geldor (1974) have derived a procedure for estimating the magnitude of convection and hindered settling and have found that the effect of the latter is minimal providing that the tube is sufficiently large and sample size is small. For a dimensionless concentration (sample volume/tube volume) of less than 10^{-4}, relative error is less than 5%. Settling convection, on the other hand, may produce a relative error of 5% for small samples of large (> 1 mm) particles or as high as 60% for large samples (> 50 grams) of small particles.

Chapman (1981) proposes a number of calibration equations which compensate for concentration effects and yield the hydraulic mean diameter of a multigrain sample (i.e. the mean diameter of quartz spheres which settle at the same median velocity as the sample). Gibbs (1972) presents a nomogram to be used for estimating the degree of error to be expected for a multigrain sample depending on particle diameter, sample weight and tube size.

SETTLING TUBE DESIGN CONSIDERATIONS

Many of the concentration effects inherent to settling analysis of sand may be minimized by careful consideration of the design of the settling tube apparatus and proper procedural guidelines. For a comprehensive review of the various design aspects of settling tubes the reader is referred to Geldof and Slot (1979) and to specific papers by Schlee (1966), Nelsen (1976), Anderson and Kurtz (1979); Riley and Bryant (1979); Amos 'et al'. (1981) and Rigler 'et al.' (1981) which describe various operating settling tube systems. The primary design aspects which must be taken into consideration are the size of the tube, the sample introduction mechanism and the detection method.

Tube length is obviously restricted by the height of the room in which the apparatus is to be housed. Gibbs (1972) suggests that minimum dimensions of 140 cm effective length and 13-16 cm inside diameter are desirable. A sufficiently long tube ensures that the particles fall at their terminal velocity over as long a distance as possible, while a large diameter reduces the wall effects created by settling in a finite medium. As a general rule of thumb, the diameter of the tube should be at least ten times that of the largest particle to be measured (Krumbein and Pettijohn, 1938).

In order to minimize concentration effects at the start of an analysis, care must be taken to employ an accurate sample introduction mechanism. Of concern here is to ensure that the sample is evenly spread over as wide an area as possible and that minimum disturbance of the suspending fluid occurs during release

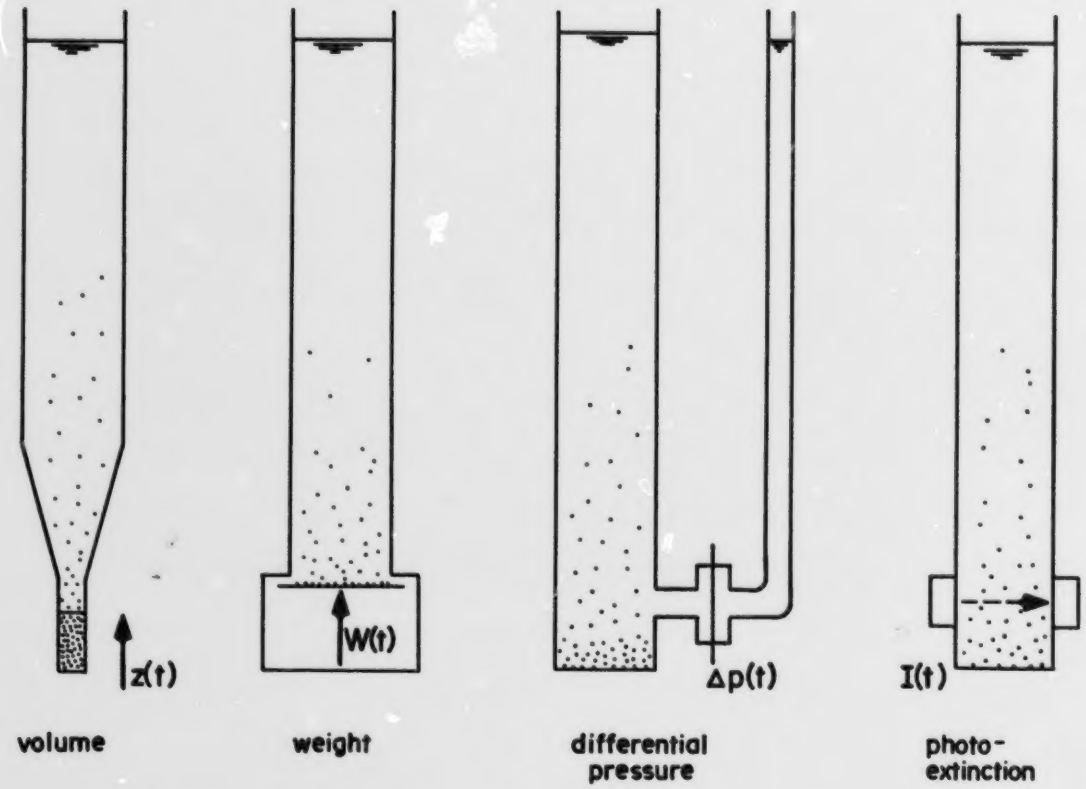

Figure 1. Common detection methods used in settling tubes (from Geldof and Slot, 1979).

of the sample. A review of the most popular types is given by Geldof and Slot (1979).

Four of the most common detection methods used for settling tubes are illustrated in Figure 1. These methods vary with respect to accuracy, cost and facility of operation. The volumetric method is the most primitive. It suffers from low resolution and a number of inherent errors which render it unsatisfactory for detailed analysis. The differential pressure method has been used by a number of laboratories (e.g. Schlee, 1966); however, it requires a relatively large sample size which leads to increased concentration effects. The weighing method is the most widely used (Riley and Bryant, 1979; Geldof and Slot, 1979; Rigler 'et al.', 1981; Amos 'et al.', 1981). It offers high resolution and sensitivity but is not without its own sources of error, most of which arise from the need to connect the weighing pan to the detection device (electrobalance or strain gauge) by a thin wire. Measurement of the arrival of particles at the bottom of the settling tube by means of interruption of a light beam (photo-extinction method) is another commonly used method for particles in the silt to clay range (Allen, 1972) but rarely used for the analysis of sand-size sediment (Taira and Scholle, 1977). It is an excellent method in terms of sensitivity and reduction of error (i.e. concentration effects and delay time) but requires frequent changing of the sedimentation fluid. For a more complete review of these four methods, their advantages and disadvantages, the reader is referred to Geldof and Slot (1979). These two authors also offer

a selection procedure to be used in order to arrive at an appropriate design based on the intended use of the system.

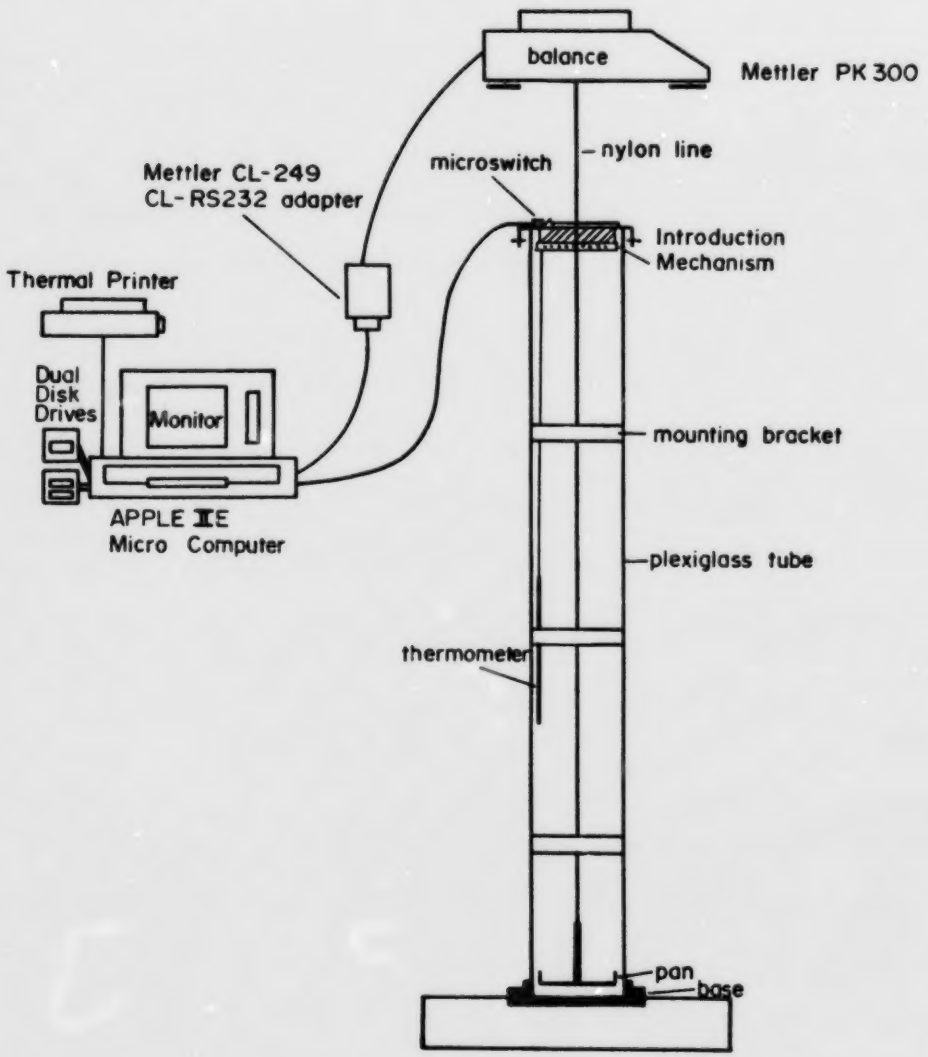

Figure 2. Configuration of C-CORE Settling Tube

CENTRE FOR COLD OCEAN RESOURCES ENGINEERING SETTLING TUBE

The C-CORE settling tube was designed and constructed with the following factors in mind: 1) type of sediment to be analysed and average size of samples; 2) suitability for routine analysis (minimum operator error); 3) a high degree of sensitivity; 4) compatibility with existing operating systems and, 5) cost. The design incorporates many of the features of the Bedford Institute of Oceanography settling tube (Amos 'et al.', 1981) with certain modifications. A complete description of the C-CORE settling tube is given in this section.

Apparatus:

The C-CORE settling tube (Figure 2) consists of a 183 cm long plexiglass tube with an inside diameter of 16.5 cm and wall thickness of 0.635. These dimensions satisfy the constraints on minimum tube size suggested by Gibbs (1972). The resulting tube volume of 3.72×10^4 cm^3 yields a theoretical error of 5% due to mass settling for a sample of 5 grams and a relative error due to hindered settling of much less than 1% for the same sample size (Kranenburg and Geldof, 1974). The tube has a flat base which rests on an X-brace with four adjustable feet for levelling. It is strapped onto a wooden frame which is in turn bolded to the laboratory wall. Both the walls and floor of the laboratory in which the tube is housed are concrete thus reducing external mechanical disturbances to a bare minimum.

Sample detection is carried out by the weighing method. A Mettler PK-300 electrobalance which has an accuracy of ±.0005

grams is mounted on a rigid platform above the tube. The sample collection pan is suspended from a bottom weighing hanger beneath the balance by a single nylon line. The sample collection pan is constructed of plexiglass and has a diameter 2 cm less than the inside diameter of the tube. This ensures that particles falling close to the walls of the tube, and hence subject to wall effects, will not be measured and assumes that statistically equal portions of all size ranges within a sample are capable of passing between the pan and the tube wall during any given run (Amos 'et al.', 1981 ; Rigler 'et al.', 1981). The plexiglass pan is almost neutrally buoyant and very stable. A heavier brass pan used initially was found to oscillate with a regular periodicity (micro-sieching) and hence was unsatisfactory. The room in which the tube is housed is under constant temperature control and, when necessary, a small fan is used to ensure that the air in the room does not become thermally stratified. This reduces thermal convection in the sedimentation fluid to a negligible level.

A venetian blind mechanism identical to that used by Amos 'et al.', (1981) is used for sample introduction (see Figure 3). It is of brass construction and was manufactured by the Technical Services Division at Memorial University. The blinds have flat, polished surfaces and semi-circular bottoms which minimize disturbance of the water when the sample is released. A small slot is cut in the middle blind through which the nylon line connecting the pan to the balance passes. The release mechanism platform is submerged approximately 1 cm below the water surface.

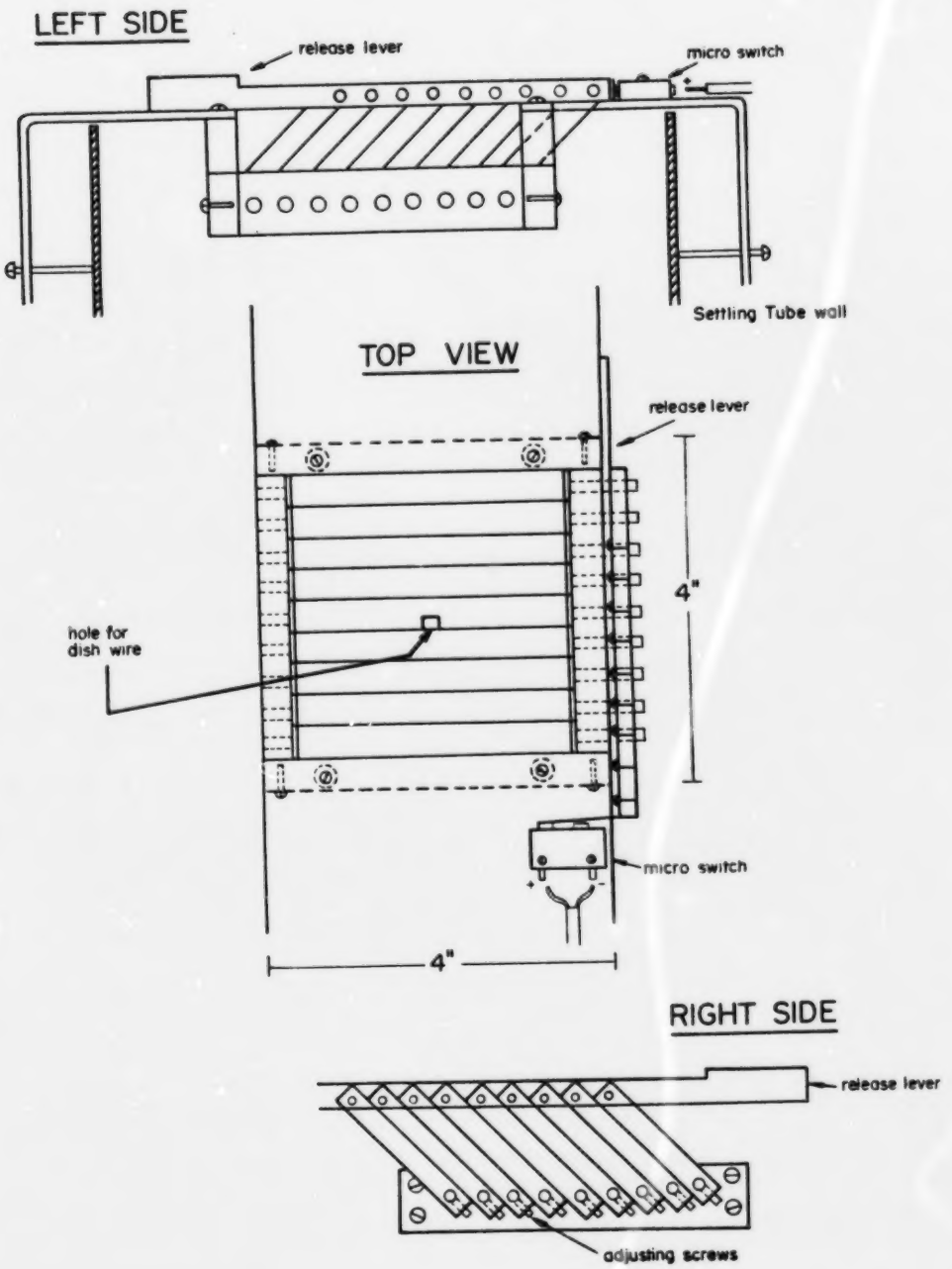

Figure 3. Venetian blind introduction system.

The sample is spread evenly over this surface and then released by manually opening the blinds. Use of a hydraulic plunger for this purpose was found to be superfluous by Amos 'et al.', (1981) (K. Asprey, pers. comm., 1983). Preliminary tests of our device have shown that some disturbance of the sedimentation fluid does occur upon sample release (Figure 4). However, this disturbance is short-lived and the drift it produces in the balance is stabilized well before the first particle reaches the pan (Figure 4). A small microswitch mounted on the release mechanism activates data logging as soon as the sample is released. Recording of data does not begin until just before the largest particle reaches the pan. In this way no spurious data produced by drift in the system is recorded.

The computer used to collect the data from the balance is an Apple IIe micro-computer, equipped with two disk drives and a thermal printer. The computer is also equipped with an Apple Super Serial Card (SSC), and a 'Thunder Clock' real time clock card. The computer communicates with the balance through a Mettler CL-249 RS-232 interface.

The clock is not used to time each point, but is used as a check of the overall time of the run, the timing of each point being intrinsic in the 0.4 second transfer rate of the balance. If the difference between actual time of the run and the calculated time is greater than 1.0 second, the user is warned of a possible timing error.

The release mechansim is fitted with a micro-switch to detect the opening of the mechanism, and connected to a switch

input on the Game IO port on the Apple.

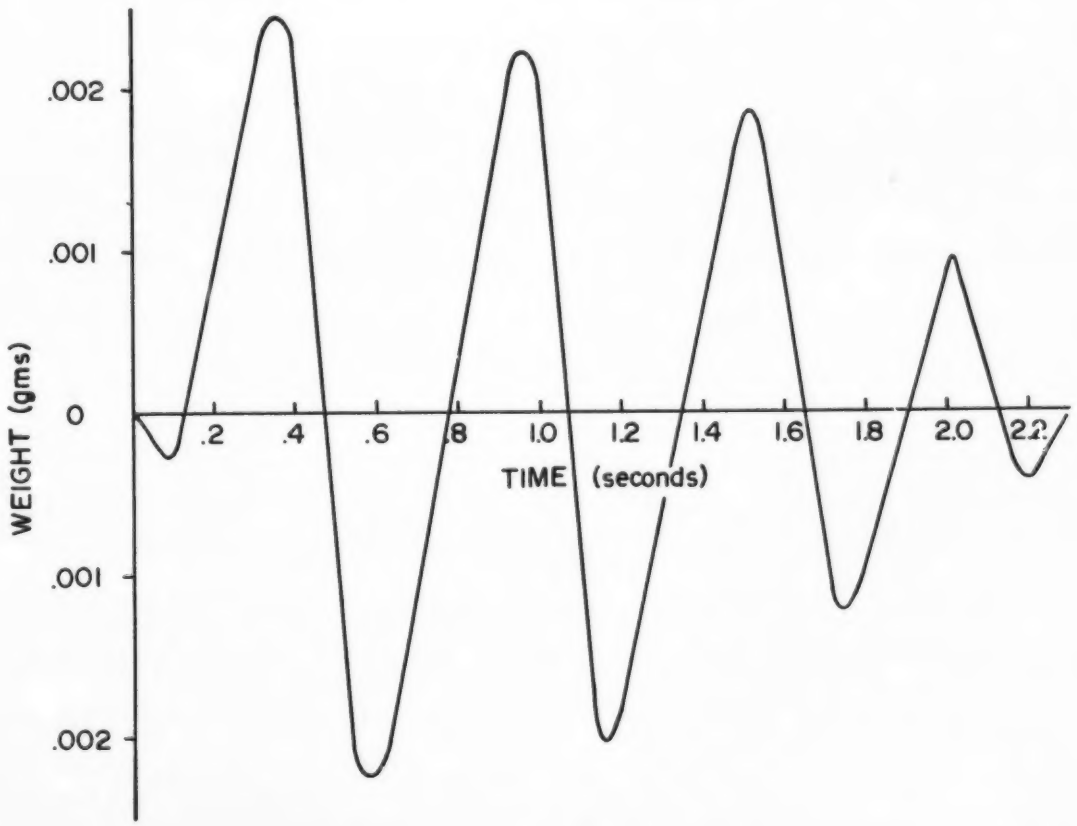

Figure 4. Graph illustrating system drift and stabilization following sample release.

Data Logging and Processing Procedure

Grain-size analysis by the C-CORE settling tube system is carried out in two stages. Initially, the prepared sample is run and the data logged by the computer is stored. Subsequently this stored data is processed to yield grain-size distribution curves and relevant grain-size statistics for each sample. Logging and processing the data for one sample takes approximately 15 minutes. However, time can be saved if a batch of samples is first logged and the data stored and then processed overnight. Approximately 70 samples may be stored on a single disk. Data logging and analysis software are available on floppy disk from the Ocean Engineering Information Centre, Memorial University, St. John's, Newfoundland, A1B 3X5, for a nominal fee.

The procedure for running the data logging and data analysis programs is outlined below.

NOTE: Disk Drives:

The Apple IIe computer has two disk drives. Both the data logger and the processor use drive 1 for their data files. This means that if the operator wishes the data files to go to the program disk, only drive 1 need be used. However, if the operator plans to run numerous data files, probably it would be better to initialize a disk for these data files only. In this case, the program disk would go in drive 2 and the data disk in drive 1.

To initialize a new disk insert the program disk into drive 2, and the new disk into drive 1, then type the following commands:

]LOAD LOGIN,D2

]INIT LOGIN,D1

The data disk is now ready. To get a list of the files on a disk, type

]CATALOG,D1 OR]CATALOG,D2

where D1 or D2 indicates the disk the operator would prefer.

Data Logging Program

The data logging program, **LOGGER**, after getting the required information from the user, calculates the range of phi sizes for which it will record data, and the phi size of each data point using Gibbs 'et al.', (1971) equation. After sensing the release through the micro-switch, it stores the data sent by the balance in its memory. When the run is completed, it saves the % weight (calculated from the dry weight input by the user), along with the calculated phi size in a text file on disk 1.

To run the data logging program, type:

]RUN LOGGER,D1 OR]RUN LOGGER,D2 (if program disk is in drive 2)

NOTE: This program should not be run while the 80-column card is active. If you have an 80 character width screen, press **ESC** followed by **Q** while pressing **CTRL** before running the program.

The program will then poll the user for the following information:

SAMPLE NAME > This is the file name for the data file. The name may contain any characters except commas, and must start with a letter. The sample name must be specified, or the program will not continue.

**(Any errors in typing may be erased with the left arrow key, and then re-typed).

DESC > This is an optional additional description of the file. (The filename must be unique; additional information can be stored in **DESC**). To omit this step, press **RETURN.**

DRY WEIGHT > This is the dry weight of the sample, and must be specified.

The following are parameters used by the program to calculate settling velocities and grain size, and to determine the range of phi sizes for which data will be logged. The default values are listed on the screen to the left of each name. To leave the value unchanged, press **RETURN.**

HEIGHT OF COLUMN >

WATER TEMP >

MAX SIZE >

MIN SIZE >

The program will now take a minute or two to calculate the phi size of each logged data point. The operator should ensure that the sample is ready, and the switch on the release mechanism is fully closed. The program will not proceed to the data logging section until the switch is closed.

The program is now ready to begin the run, and will start as soon as the sample is released. The first few transmissions from the balance will be ignored, since sediment will not have reached the pan. The number of transmissions to be ignored is determined by the maximum grain size specified by the user. The message **"DATA LOGGING STARTED"** will appear on the screen just prior to

the largest particle striking the pan. If any sediment has already landed on the pan at this time, then the sample will contain grains larger than the maximum size specified earlier. The operator should make the run again and specify a larger maximum grain-size. During the data logging process it is imperative that movement in the lab be kept to a minimum so as not to disturb system stability.

The total number of points and the time for the run are given at the top of the screen. The line in the centre of the screen contains information about data logging. The first number is the number of the data point, followed by the value transferred from the balance. The two numbers following this are the transmission number and the number of transmissions for each point. Throughout the run, the balance transfers a value every 0.4 seconds. At the coarse end of the run, each transmission is logged, but at the finer end as many as 150 transmissions are taken for a single data point. The reason for this is as follows:

In the early stages of program development it became clear that some method would have to be used to vary the number of transfers per data point logged. Due to non-linearity of the grain-size settling velocity relationship for grain sizes smaller than 3.0 phi, more than 125 transfers would be logged in a single 1/4 phi interval if every transfer was recorded. A method was devised for the computer to calculate the optimum number of transfers for each data point, and require the operator only to input the range of sizes of interest. These intervals

are calculated by first determining the minimum number of transfers per point required within each 1/4 phi range to provide 1/20 phi discrimination. This works out to be roughly 4-5 points logged for each 1/4 phi range. Due to the efficient interface between Basic and Assembly languages, there is no problem logging transfers at rates as low as one every 0.1 second. The phi system is used within the program as this logarithmic scale is most representative of the discrimination required by geologists. If desired, the units could easily be converted to metric, Imperial or chi (May, 1981) values for input and output. In addition, a listing of settling velocities may be obtained.

When the run is finished, the data will be saved on the disk, and the actual time for the run will be displayed. The timing of the run is intrinsic in the 0.4 second transfer rate of the balance, but this is checked for the entire run by a clock inside the computer. If the calculated and actual values differ by more than one second, an error message will be printed on the screen. If this should happen, make the run again.

The operator may now make another run, or go on to the analyser program. Once a program has been loaded (**]RUN LOGGER**), it need not be reloaded until another program is run. If the operator wishes to make another run simply type:

]RUN

Data Processing Program

The processing program, **PROCESSOR**, gets the data file created by the data logger and calculates the mean grain size, standard deviation, skewness, and kurtosis and plots a graph of the grain size distribution. Grain size statistics are calculated using the method of moments.

To run the data processor, type:

]RUN PROCESSOR,D1 or **]RUN PROCESSOR,D2**

The program will ask the operator for the name of the data file. This is the same name the operator entered for **SAMPLE NAME**, and appears at the top of the screen during the actual data logging. Given this, the program will load the data from the disk, and then ask:

DO YOU WANT HARDCOPY?

If the operator would like the information to be printed out on the printer, answer **Y**; if the operator only wishes to view it on the screen, type **N**, or **RETURN**.

The data logger logs about 5 data points for every 1/4 phi interval, and the statistics are done from this data set. The data is then condensed into 1/4 phi intervals, and listed on the printer or screen. The operator has the option of graphing either the full data set (approx. 1/20 phi intervals), or the condensed data (1/4 phi interval). The program will ask:

INTERVAL FOR GRAPH:

(1) 1/4 phi (2) 1/20 phi >

If the operator types 1, the condensed data will be graphed, or if the operator enters 2 (or **RETURN**) the full data set is

displayed.

If the operator requests that the information be shown on the screen, rather than the printer, the program will pause after listing the data and after finishing the graph. Press any key to continue the program.

If the operator would like a hardcopy of the graph only, press **P** when the graph is completed.

Overnight Processing

If desired, time can be saved by running only the data logger for each sample during working hours, and then running the processor overnight. There are two programs that can be used for overnight processing: **SUBMIT** which submits a single sample to be processed, and **DISK DUMP** which processes all the text files on a disk.

Both these programs use a file called **PRINTJOB**, which contains a list of commands to process each sample. **SUBMIT** adds a new sample to the list each time it is run, until the time comes to process the samples using **PRINTIT**, which starts the processing, and when it is done, deletes the file **PRINTJOB**.

An example of its use follows:

```
]RUN SUBMIT
FILE NAME>TEST DATA 1              TEST DATA 1 added to list,
]RUN
FILE NAME>TEST DATA 2              TEST DATA 2 added to list,
]RUN PRINTIT                       processing begins ...
```

DISK DUMP reads the directory of the disk and submits all

text files on the disk. Remember, any test files other than sample files will also be submitted and could cause errors during the processing. Thus, **DISK DUMP** should be used on disks that contain only sample files.

A disk will hold approximately 70 samples, and this takes almost a full roll of paper, so it is wise to check the roll before starting the processing.

System Calibration

Upon completing the construction of the C-CORE settling tube, a number of controlled runs were made in order to test and document the range of parameters, including particle size and sample size, measurable by the system and the accuracy and reproducibility of the system within this range. No attempt was made to replicate the intensive tests carried out by Gibbs 'et al'., (1971). It has been assumed that the C-CORE settling tube would yield equivalent results (within reasonable limits) to those of Gibbs 'et al.' (1971) since tube dimensions are within the acceptable limits suggested by Gibbs (1972) and all other factors are equal. It is suggested here that the scatter in results of ± 20 microns noted by Amos 'et al'. (1981) when attempting to duplicate the tests of Gibbs 'et al'. (1971) most likely arise out of imperfections in shape and density of the glass beads chosen rather than some "higher order harmonic effect which is not accounted for in the Gibbs transformation" (Amos 'et al'., 1981, p.27).

Since all the samples run during our calibration tests were multigrain samples, they closely approximate "real" conditions and incorporate all or the errors inherent in multigrain settling (concentration effects). In all, three types of materials were tested--commercial glass beads, crushed quartz blasting sand, and samples of well sorted and poorly sorted continental shelf sands from the Grand Banks of Newfoundland.

(i) Grain Size Limits:

Certain physical limitations restrict the range in sediment

grain size which may be analysed by the C-CORE settling tube. The maximum grain size which can be run is restricted by the length and inside diameter of the tube. As a rule of thumb, Krumbein and Pettijohn (1938) propose that the settling velocity of a particle settling in a confined cylinder will not be appreciably affected until the diameter of the particle equals one tenth of the diameter of the cylinder. This translates to a maximum grain size of 1.65 cm for the C-CORE settling tube. Results of test runs on the C-CORE settling tube suggest that for particles larger than 2 mm, settling velocities are too high to be measured accurately and particles reach the pan prior to stabilization of the initial oscillations produced by releasing the sample. For this reason, our tests suggest 2 mm is the maximum particle size which may be measured accurately with this system. Vanoni (1975) proposes a formula relating the settling velocity of a particle in a tube (W_d) to its unconfined settling velocity (W) as:

$$\frac{W}{W_d} = 1 + (9/4 \cdot d/D) + (9/4 \cdot d/D)^2$$

where d = mean grain diameter (cm) and D = tube diameter (cm) Thus, for a grain diameter of 2 mm settling in the C-CORE settling tube there would be a 2.7% reduction in settling velocity using this formula.

The tube used by Gibbs 'et al.' (1971) had an inside diameter of 12.8 cm. This is 3.7 cm smaller than the C-CORE settling tube and results in a relative error of 0.8% when applying the Gibbs 'et al.' equation for 2 mm grains. This has

been neglected in the calculation of grain size using the Gibbs 'et al.' formula.

The smallest grain-size measurable on a routine basis using the C-CORE settling tube is dependent primarily upon convenience. Basically, the smaller the particles, the longer the time required to complete a run. For this reason 63 microns has been chosen as the smallest size to be run. As such, the range in grain-sizes measurable with the C-CORE settling tube encompasses sediment of all sand sizes.

(ii) Glass Bead Calibration:

To test both the accuracy and reproducibility of the C-CORE settling tube system a number of runs were made using subsamples of glass beads ranging in size from 850 microns to 74 microns. Glass beads were generously provided by Flex-o-lite (Canada) Limited, pre-sieved into size fractions guaranteed to vary by not more than ±10 percent. Results of the calibration runs are listed in Appendix A. These results reveal a high degree of reproducibility when measuring mean grain size and sorting; skewness and kurtosis are less reliable measures on a routine basis. Mean grain-sizes measured with the settling tube compared favourably with the median size of each sieved sample, within the allowable limits of error. This indicates a high degree of accuracy for the C-CORE settling tube system since, for spherical particles, sieve diameter and settling diameter should be equal (Gibbs 'et al.', 1971). Any incongruities can only result from irregularities in the shape of the glass beads or concentration effects as described earlier (see Chapman, 1981).

(iii) Crushed Quartz Calibration

As natural sediment grains are generally somewhat less than spherical, a test of the accuracy of the C-CORE settling tube for non-spherical particles was required. To this end, a sample of crushed quartz, characterized by extreme angularity and non-sphericity, was sieved for one half hour at 1/2 phi intervals and subsamples of 1-5 grams from each of these intervals were run. The results of these runs are tabulated in Appendix B. These results indicate a high degree of reproducibility, especially for mean grain diameter and sorting. The moment measures (skewness and kurtosis) are less reliable on a routine basis for particles larger than 1 mm and smaller than 90 microns, although kurtosis would appear to be much more reliable than skewness.

Comparisons are made between the measured mean grain diameter and the median of each phi interval, although it is felt that this is an obvious "apples and oranges" situation as pointed out by May (1981). In general, however, the two compare well although there is a consistent tendency to underestimate grain size for the larger intervals using the settling tube. Most likely this is caused by the extremely non-spherical nature of the larger grains which reduces their settling velocity and hence their apparent size. Baba and Komar (1981) have found that irregularities in grain shape are much more critical than grain roundness (angularity) when measuring settling velocities. These perturbations in grain character and the sensitivity of the settling tube to them are what make this method particularly suited to interpretation of hydraulic conditions in the

environment of deposition (Reed 'et al.', 1975; Bridge, 1981).

(iv) Sample Size Calibration:

As with the sieve method, there is an optimum sample size which may be measured by the settling tube method. In theory, samples may be as small as one grain; however, this one grain would not be representative of any larger population. Amos 'et al'., (1981) present a nomogram for estimating the number of grains of a given size in a sample of a given weight (see Figure 5). As an example, a dry sample weighing 1 gram and containing 1% coarse sand (> 1000 microns) would contain less than 10 particles in that size range and therefore would be non-representative of the population distribution. In addition to this consideration, splitting a small subsample from a larger population involves inherent errors as well. At the other end of the scale, the maximum size of sample which can be used is restricted by concentration effects (mass and hindered settling).

As a test of the optimum sample size to be used in the C-CORE settling tube, a series of subsamples of poorly sorted and well sorted coarse sand from the Grand Banks of Newfoundland were run. Results of these runs are shown in Tables 1 and 2.

Optimum sample weights were determined to be 3-10 grams for both samples. Above these weights, mass settling and convection were observed while below these weights scatter in the results due to splitting errors are evident. (Subsample splitting was carried out by the cone and quarter method).

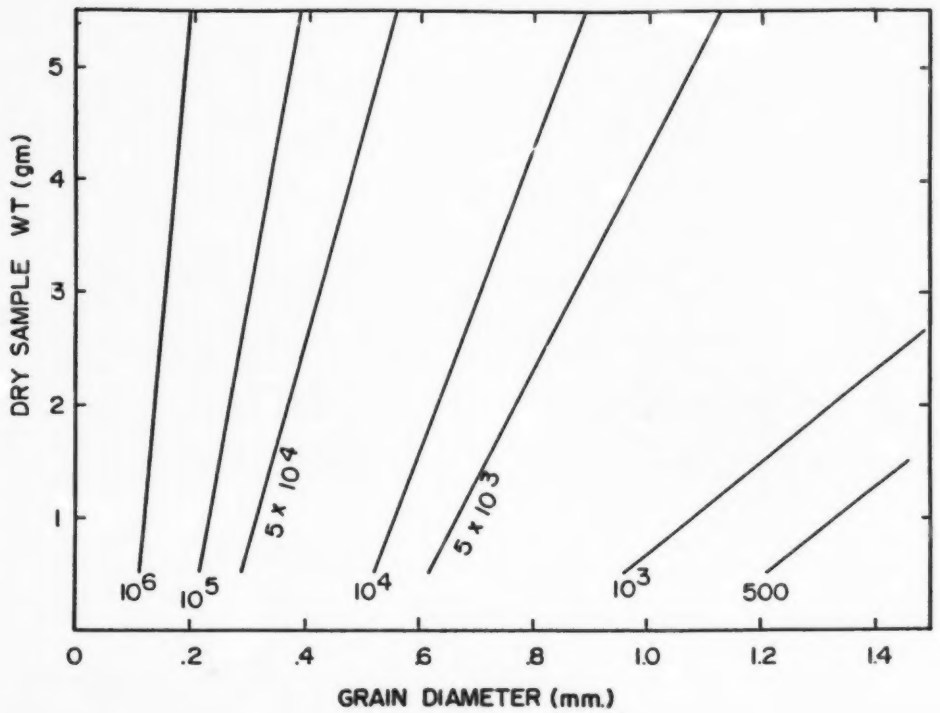

Figure 5. The number of grains per dry weight of sample for a range of sizes 100-1400 microns.

(v) Calibration Summary:

All test runs performed indicate that the C-CORE settling tube system demonstrates a high degree of sensitivity, accuracy and reproducibility on a routine basis. Observed discrepancies between sieve and settling results are believed to be both real and significant. They do not in any way reflect on the accuracy of the settling tube system but rather highlight the differences in grain parameters measured by each method.

TABLE 1: Sample size calibration results: well sorted Grand Banks of Newfoundland sand.

Dry Weight (gm)	Mean (ø)	Mean (mm)	Sorting	Skewness	Kurtosis
0.3	1.22	.43	.50	3.06	19.46
0.5	1.15	.46	.43	.96	17.42
1.2	1.23	.42	.48	-.32	11.31
1.4	1.34	.39	.43	.17	11.28
2.0	1.26	.42	.42	.40	8.93
2.5	1.19	.44	.39	.76	10.80
3.0	1.20	.43	.38	.71	7.29
3.3	1.23	.42	.39	.58	8.38
4.3	1.30	.40	.38	.25	7.33
5.2	1.22	.43	.40	.16	5.83
5.6	1.24	.42	.41	-.14	5.84
6.2	1.28	.41	.38	.23	5.81
6.7	1.31	.40	.39	.15	5.78
7.5	1.31	.40	.38	-.08	5.14
8.5	1.23	.42	.40	-.15	4.28
10.4	1.25	.42	.44	-.04	4.03
12.4	1.23	.42	.42	.27	4.56
15.0	1.26	.42	.37	.44	4.61
20.2	1.19	.44	.40	.30	4.49
25.0	1.24	.42	.39	.33	4.56

TABLE 2: Sample size calibration results: poorly sorted Grand Banks of Newfoundland sample.

Dry Weight (gm)	Mean (ø)	Mean (mm)	Sorting	Skewness	Kurtosis
0.3	1.46	.362	.75	.50	2.73
0.6	1.32	.400	.66	.40	3.89
1.3	1.76	.298	.67	-.54	3.11
1.7	1.72	.305	.70	-.55	2.83
2.2	1.75	.300	.70	-.58	2.63
3.0	1.54	.344	.76	-.21	2.49
3.8	1.46	.362	.83	-.14	1.82
4.6	1.58	.335	.76	-.23	2.16
5.0	1.45	.365	.72	.11	2.24
5.5	1.44	.367	.78	9.65	1.96
6.0	1.57	.340	.77	-.12	2.15
7.0	1.52	.350	.78	-.05	1.94
7.6	1.5i	.352	.79	-.08	2.05
8.5	1.46	.362	.81	-.10	2.07
8.9	1.48	.360	.79	3.2	2.01
10.0	1.49	.355	.80	-.05	2.02
12.6	1.36	.387	.81	.10	1.95
15.0	1.40	.379	.82	.05	1.99
17.3	1.48	.360	.81	.07	1.85
20.0	1.47	.362	.79	-.04	2.04

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*Operating settling tube systems.

APPENDIX A

GLASS BEAD CALIBRATION TESTS

Bead Size (mm)	Dry Weight (gm)	Mean (mm)	Sorting	SK	K
.840-.567	5	.63	.03	.38	1.60
	5	.61	.03	-1.43	-16.30
(avg.= .704)	4	.61	.03	.76	7.12
±10%	4	.61	.03	-.02	3.44
	3	.61	.03	.80	6.94
	3	.62	.03	.83	11.56
	2	.61	.03	.59	10.38
	2	.62	.02	-2.60	-59.11
	1	.62	.03	-.02	14.23
	1	.62	.03	.59	3.78
.567-.419	4	.47	.03	.27	2.32
	4	.47	.04	.55	2.86
(avg. = .493)	3	.48	.04	.37	2.56
±10%	3	.47	.04	.48	2.73
	2	.48	.04	.26	2.35
	2	.47	.04	.36	2.57
	1	.48	.04	.55	2.28
	1	.48	.04	.53	2.21
.297-.211	3	.26	.02	1.07	7.67
	3	.27	.03	1.70	7.41
(avg. = .254)	2	.27	.02	2.71	12.16
±10%	2	.27	.03	2.08	8.11
	1	.27	.03	1.85	6.35
	1	.28	.04	1.61	4.96
	1	.29	.04	1.04	3.00
.211-.150	3	.17	.01	.37	4.91
	3	.17	.02	-.70	4.15
(avg. = .181)	2	.17	.01	-.51	4.52
±10%	2	.17	.02	-.84	3.78
	2	.17	.02	-.58	3.78
	1	.16	.02	.06	4.80
	1	.17	.02	.03	4.10
	1	.17	.01	-.18	3.72

Bead Size (mm)	Dry Weight (gm)	Mean (mm)	Sorting	SK	K
.150-.089	3	.12	.02	-.62	3.23
	3	.12	.02	-.68	2.92
(avg. = .120	3	.12	.02	-.53	3.12
±10%	2	.12	.02	-.49	3.61
.150-.089	2	.12	.01	-.20	3.95
	2	.12	.02	-.45	3.55
(avg. = .120)	1	.12	.01	-.34	4.93
± 10%	1	.12	.01	-.69	4.58
.124-.074	5	.10	.02	.05	2.11
	4	.10	.02	.09	2.52
(avg. = .099)	4	.09	.02	-.18	2.40
± 10%	4	.09	.02	-.36	2.33

APPENDIX B

CRUSHED QUARTZ CALIBRATION TESTS

Sample (mm)	Weight (gm)	Mean Ø	Mean (mm)	Sorting	Skewness	Kurtosis
2.0-2.4	4	-.18	1.10	.12	.03	.38
1.4-2.0	2	-.12	1.05	.10	-.20	-1.82
(median	2	-.10	1.04	.16	.23	3.32
= 1.7)	3	-.08	1.02	.12	-.49	-1.62
	3	-.10	1.04	.15	.19	3.95
	4	-.08	1.02	.15	-.29	3.30
	4	-.02	1.01	.14	.21	3.13
1.0-1.4	2	.24	.83	.14	.13	2.47
(median	3	.29	.85	.13	.05	3.27
= 1.2)	3	.28	.84	.14	.03	3.18
	4	.29	.85	.13	.12	4.64
	4	.29	.85	.14	.62	3.60
	5	.29	.85	.12	-.21	2.09
	5	.27	.84	.12	-.52	.47
	10	.25	.83	.12	-.37	.63
	10	.28	.84	.13	7.03	2.87
.710-1.0	2	.58	.66	.14	-.13	3.59
(median	2	.53	.67	.12	-1.29	-4.54
= .86)	3	.60	.65	.14	-.16	2.82
	3	.64	.63	.13	-.86	2.80
	4	.61	.64	.13	-.91	.63
	4	.61	.64	.14	-.53	1.66
	5	.61	.64	.14	-.42	2.67
	5	.62	.64	.15	-.17	4.39
	10	.61	.64	.13	-.37	1.51
	10	.63	.63	.14	-.06	3.38
.500-.710	2	1.00	.50	.13	-.21	4.88
(median	2	.96	.51	.12	-.51	4.29
= .61)	3	1.00	.50	.13	-.14	3.91
	3	1.00	.50	.13	-.04	4.42
	4	1.00	.50	.13	4.66	4.70
	4	.98	.50	.12	-.15	3.42
	5	.98	.50	.13	.05	4.70
	10	.99	.50	.12	.46	4.52
	10	1.01	.50	.13	.56	4.95

.355-.500	2	.43	.03	-.34	3.19
	2	.43	.03	-.18	3.44
(median	3	.44	.03	-.37	4.09
= .427)	3	.43	.03	.03	3.50
	4	.43	.03	-.10	3.62
	4	.43	.04	-.14	3.45
	5	.43	.04	-.25	3.76
	5	.43	.03	-.34	3.62
	10	.43	.03	-1.02	3.79
	10	.44	.04	-.57	3.52
.250-.355	2	.30	.03	.41	3.63
	2	.29	.03	.67	3.92
(median	3	.31	.03	-.09	3.07
= .307	3	.32	.03	-.31	3.44
	4	.32	.03	-.45	3.21
	4	.30	.03	-.31	3.28
	5	.30	.03	-.45	3.34
	5	.30	.03	-.43	3.28
	7	.30	.03	-.49	2.90
	7	.31	.03	-.49	3.14
.177-.250	2	.23	.02	-.46	3.75
	2	.22	.02	-.36	3.84
(median	3	.23	.02	-.87	3.47
= .213)	3	.23	.02	-.80	3.60
	4	.23	.02	-.84	3.66
	4	.24	.02	-.85	3.88
	5	.23	.02	-.68	3.51
	5	.23	.02	-.74	3.55
	7	.24	.02	-.79	2.88
	7	.24	.02	-.62	2.99
.125-.177	2	.17	.02	-.67	3.46
	2	.18	.02	-.60	3.82
(median	3	.18	.02	-.72	3.34
= .151)	4	.18	.02	-.76	3.59
	4	.18	.02	-.61	3.28
	5	.18	.02	-.60	3.25
	5	.18	.02	-.47	3.09
	7	.19	.02	-.59	3.00
	7	.19	.02	-.56	2.68
.063-.090	2	.11	.23	1.89	7.66
	3	.13	.24	1.10	4.26
(median	3	.13	.24	1.02	4.05
= .108					

.063-.090 (median = .076)	2	.088	.32	.84	2.99